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SEARCH FOR NEW PHENOMENA AT COLLIDERS

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ABSTRACT

Recent results on searches for new phenomena on the Tevatron and HERA colliders are reviewed.

1 Introduction

In spite of the great succes of the Standard Model (SM) we still do not have a unified description of all the four known forces in a finite, renormalizable theory. Therefore new phenomena are expected beyond the SM at some energy scale M_X. Today only elements of this ultimate theory are available and are proposed for experimental tests. In the present paper I have chosen an arbitrary list of these tests addressed by two active colliders, Tevatron and HERA: *Extra Dimensions (ED), Supersymmetry (SUSY), Z', Leptoquarks, Beyond SM Higgs bosons, and Substructures of quarks and leptons.* The confrontation of these models with experiment is complemented by a *systematic search* for departures from the SM. Concerning the scale M_X, its natural value would be the Planck-mass, M_{Pl} if one is aiming at unification with gravity. However the very large value of M_{Pl}, in comparison with the electro-weak scale leads to "unnatural" fine tuning of scalar masses, known as the *hierarchy problem*. Some of the above topics present solution to this problem.

Frequently, the same event topology, like e.g. high mass lepton pairs, allows to test several theoretical models.

In the Tevatron collider at Fermilab, near Chicago, protons collide with antiprotons at a center-of-mass energy of 1960 GeV. Two experiments are collecting data, CDF and DØ. Both experiments as well as the Tevatron underwent substantial upgrades in the last decade. In the new data taking period (Run II) started in spring 2001, the Tevatron has delivered already 3 times more luminosity as in Run I. The detector upgrades allow efficient operation at the increased luminosity, provide extended coverage of subdetectors and in the case of DØ a completely new central tracking. In this paper only the most recent results from Run II will be reviewed making use of typically 200 pb^{-1} integrated luminosity.

In the HERA collider at DESY, near Hamburg, positrons or electrons collide with protons at 300 (or 318) GeV energy in the center of mass. The data are collected by two experiments, H1 and ZEUS. Here again, the collider as well as the two detectors have been upgraded. The new periode of data taking (HERA II) has started recently with the goal to collect 10 times more luminosity as in HERA I and with a possibility of using longitudinally polarized electron beam. In this paper only results from HERA I will be covered since results with comparable statistics from the new data taking period hasn't been published yet.

All limits are quoted at 95% confidence level. References for theoretical models can be found in those quoted for experimental results.

2 Extra Dimensions

As Theodor Klauza has shown the first time, almost a century ago, extra dimensions (ED) can provide a framework for unification with gravity. ED's were supposed to be compact of a very small size (Oscar Klein) since we don't sense them in our everyday experiences. Particles propagating in compact ED's have higher mass replica's, the so-called Klauza-Klein (KK) states. Recently, ED's revived interest since their existence is needed in string theories, and also because it was pointed out that their size can be large (LED), and therefore accessible for experimental verification. Moreover, LED's explain that gravity is only apparently weak and the scale of new physics can be much lower than the Plank mass, thereby avoiding the hierarchy problem.

ED's can be tested experimentally on colliders either by virtual effects or direct emission of the KK-states.

2.1 Search for LED's

LED's can be of macroscopic size if only gravity is supposed to propagate in them. Indeed, gravity experiments have tested Newton's law only down to $\sim 10^{-4}$ m distances. The *virtual effects of the graviton KK-states* show up at hadron colliders e.g. as deviation in the distribution of the invariant mass, M and that of the angle θ^* in the center of mass of di-lepton and di-photon states. DØ has studied these distributions not separating the di-electron and di-photon states [1](i). The expected deviation can be parametrized as:

$$\frac{d^2\sigma}{dM d\cos\theta^*} = f_{SM} + f_{int}\eta_G + f_{KK}\eta_G^2, \tag{1}$$

where f_{SM}, f_{KK} and f_{int} are the contributions due to the SM, KK gravitons and the interference between them. The constant η_G contains the fundamental scale of the gravitation, M_S, given e.g. by Hewett in the following form:

$$\eta_G = \frac{2\lambda}{\pi}\frac{1}{M_S^4}; \quad \lambda = \pm 1. \tag{2}$$

DØ's result is displayed in Fig. 1. The data points follow the expected background. The absence of events at high mass allowed to obtain lower limits for $M_S = 1.22$ ($\lambda = +1$) and $M_S = 1.10$ ($\lambda = -1$). Similar conclusions have been obtained by CDF [2]: $M_S = 0.961$ ($\lambda = +1$) and $M_S = 0.987$ ($\lambda = -1$). At HERA one has compared the inclusive neutral current (NC) deep inleastic cross sections to that expected from the SM. As no deviation has been found (see e.g. Fig. 2a) both experiment established
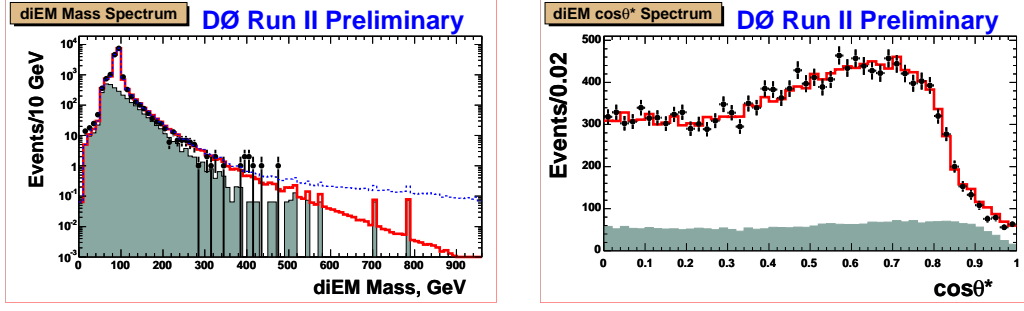
Figure 1: *The invariant mass (left) and angular distribution (right) of di-electron and di-photons obtained by DØ . Points with error bars are the data; light filled histogram represents the instrumental background, solid line shows the fit to the sum of the instrumental background and SM predictions. The dashed line shows the effect of the LED signal for $\eta_G = 0.6$.*

limits on M_S (using $\eta_G = \frac{\lambda}{M_S^4}$), H1: $M_S = 0.82$ ($\lambda = +1$) and $M_S = 0.78$ ($\lambda = -1$) [3](i), ZEUS: $M_S = 0.78$ ($\lambda = +1$) and $M_S = 0.79$ ($\lambda = -1$) [4](i).

 Direct emission of KK gravitons have been searched for on the Tevatron by both collaborations. The signature is a monojet, i.e. a jet of high transverse energy (E_T) accompanied by a large missing transverse energy (MET). No significant number of such events above the expected backgorund has been found. The present limits on the fundamental scale of the gravitation (M_d) as a function of the number of ED's is given in Fig. 2b [1](ii).
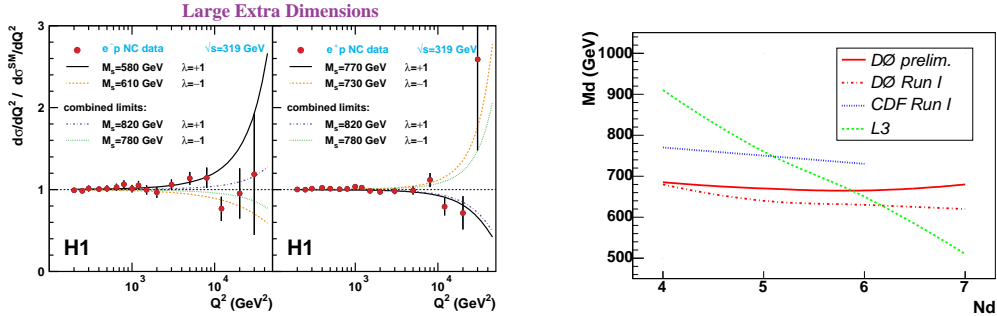

Figure 2: *(a) NC cross sections obtained by H1 at $\sqrt{s} = 319$ GeV normalized to the SM expectation (left). (b) The present limits on the fundamental scale of the gravitation (M_d) as a function of the number of ED's (right) obtained at the Tevatron in the monojet channel.*

4

2.2 Search for TeV^{-1} size LED

DØ has searched for TeV^{-1} size LED in a model where fermions are confined in the ordinary $3d$ world, in contrast to gauge bosons which can propagate in an extra compact dimension. Such a possibility can lead to spectacular minima and secondary maxima in the di-lepton invariant mass distribution due to the interference of the KK states of gauge bosons. The absence of such behaviour in the di-electron channel allowed to set a lower limit of 1.12 TeV for the inverse size of the ED [1](iii).

2.3 Search for Randall-Sundrum resonances

CDF has searched for graviton resonances predicted by the Randall-Sundrum model in the mass distribution of di-lepton pairs. Fig 3a shows the data and the expected background for the muon pairs. Since data and background are in agreement and no resonant structure is observed, CDF has established limits on the resonance mass as a function of the model parameter, k (Fig. 3b) [2].
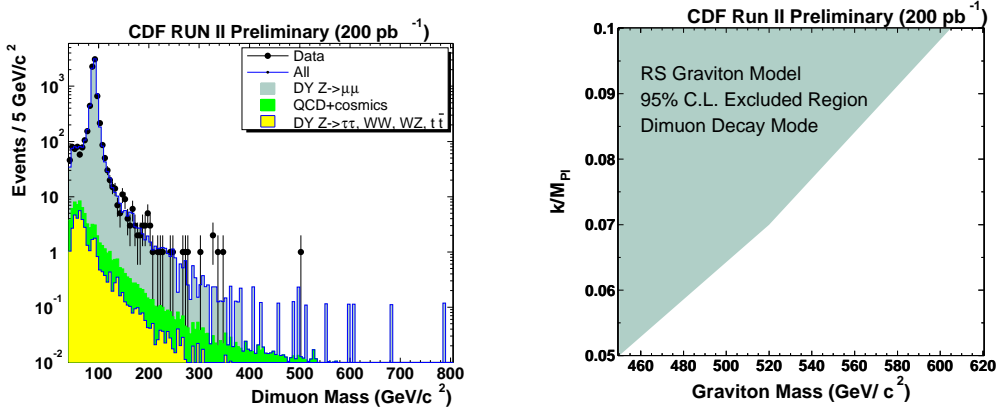

Figure 3: *(a) Invariant mass distribution of opposite sign muon pairs observed by CDF (left) together with the estimated background. (b) Limit on the mass of Randall-Sundrum graviton resonances as a function of the model parameter k (right).*

3 Supersymmetry (SUSY)

SUSY is a symmetry of Nature with respect to interchange of bosons and fermions. It is a basic ingredient for unification with gravity (e.g. in Superstring/M-theories). It is also the only non-trivial extension of the Lorentz-Poincaré group. Moreover, it presents an elegant solution for the hierarchy problem. In the minimal supersymmetric extension of the SM (MSSM), every SM particle has a SUSY partner whose

spin differs by $\pm 1/2$. R-parity, defined as $R = (-1)^{3B+2L+S}$, where B, L and S are the baryon number, lepton number and the spin, is $+1$ for SM particles and is -1 for their SUSY partners. Apart of the SUSY partners a second Higgs doublet is also needed in the MSSM. Its mass parameter represents the only additional parameter in the theory if SUSY were an exact symmetry.

SUSY is however a broken symmetry, at least at the electro-weak energy scale, which introduces more than a hundred new parameters. With additional hypotheses one can reduce this number to a managable size: 5 (m_0, $m_{1/2}$, $\tan\beta$, sgnμ and A_0) for the gravity mediated symmetry breaking model, mSUGRA, and 6 (Λ, M_m, N_5, $\tan\beta$, sgnμ, and C_{grav}) for the gauge mediated symmetry breaking model, GMSB, considered here [5].

R parity is approximately conserved in order to avoid B and L violating processes. In this case SUSY partners are pair-produced and the lightest SUSY particle (LSP) is stable. Since it is believed to be neutral and it interacts weakly, the basic experimental signature for SUSY is large MET. It is accompanied by several leptons and jets from cascade decays of SUSY particles. The main SM background is $t\bar{t}$ and gauge boson pair production.

However small R parity violation cannot be excluded which allows single resonant formation of the SUSY partners and gives rise to more leptons and jets in the final state due to the decay of the LSP. At Tevatron both R parity conserving (RPC) and R parity violating (RPV) processes can be studied. HERA is competitve only in RPV SUSY searches.

3.1 RPC SUSY searches at the Tevatron

For this kind of searches the golden channel is chargino-neutralino pair production where the large MET is accompanied with several leptons. DØ has used the $e-\mu-l$, $e-e-l$ and $\mu^{\pm}-\mu^{\pm}$ signatures, where l stands for a lepton having a charged isolated track. LEP has already set stringent limits in the mSUGRA parameter space for these processes. DØ has therefore investigated the region of $72 \leq m_0 \leq 88$ GeV, $165 \leq m_{1/2} \leq 185$ GeV, $\tan\beta = 3$, $\mu > 0$, $A_0 = 0$. This region is situated above the LEP limits and is characterized by the mass relations $m_{\chi_1^{\pm}} \approx m_{\chi_2^0} \approx 2m_{\chi_1^0} \approx m_{\tilde{l}}$ offering the highest discovery potential. In all three channels the number of candidate events has been found compatible with that estimated from the SM background in the kinematical regions where the expected signal is dominant. This allowed to obtain upper limit of appr. 0.5 pb for the production cross section times branching ratio above the chargino mass limit established by LEP (≈ 103 GeV).

This limit is a considerable improvement with respect to that obtained in Run I but is slightly higher than the mSUGRA prediction (≈ 0.3 pb) [1](iv).

The signature of *s*quarks and gluinos are multiple jets and MET. As shown in Fig 4 signal and background can be well separated using MET and HT, where this latter is the scalar sum of the jets. Since the data points are dominantly in the
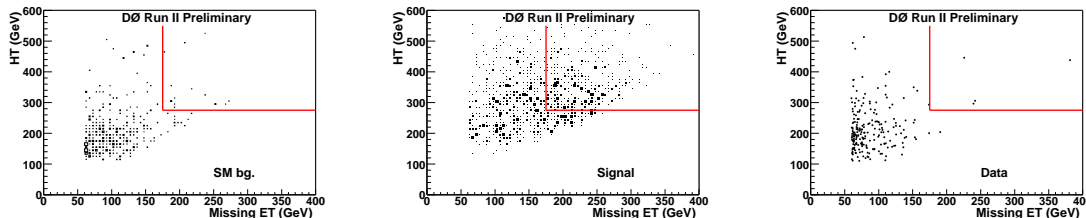

Figure 4: *Expected SM background (left), squark/gluino signal (middle) and observed data by DØ in the HT vs MET plot (right).*

background region, *s*quarks and gluinos have been excluded by DØ below masses $m_{\tilde{q}} < 292$ and $m_{\tilde{g}} < 333$ GeV, respectively, in the mSUGRA parameter space of $m_0 = 25$ GeV, $100 \leq m_{1/2} \leq 140$ GeV, $\tan\beta = 3$, $\mu < 0$, $A_0 = 0$ [1](v).

In the GMSB model the LSP is a very light gravitino. Assuming that the next LSP is the lightest neutralino, which decays promptly to a photon and a gravitino, CDF [2] and DØ [1](vi) searched for events with 2 isolated photons accompanied by MET. Both experiments found that the MET distribution was in agreement with the expected background (Fig 5a). This allowed to set limit on the SUSY breaking scale $\Lambda > 78.8$ TeV as shown e.g. in Fig 5b.

3.2   RPV SUSY searches

R parity violation introduces 48 new unknown Yukawa couplings, λ_{ijk} in the Lagrangian:

$$L = \lambda_{ijk} L_i L_j \tilde{E}_k + \lambda'_{ijk} L_i Q_j \tilde{D}_k + \lambda''_{ijk} U_i D_j \tilde{D}_k, \tag{3}$$

where i, j, k are the generation indices and $L, (E), Q, (D)$ are isodoublet (isosinglet) lepton and quark super-fields, respectively [5]. At HERA the production and decay of *s*quarks have been searched for in different final states. The absence of the expected resonant peak has been transformed to exclusion of the λ'_{1j1} coupling and other SUSY parameters. An example is shown in Fig. 6a [3](ii). At the Tevatron, CDF searched for a peak in the opposite sign dilepton distribution as signature of the formation and decay of $\tilde{\nu}$ [2]. The absence of the peak excludes $\tilde{\nu}$ masses and λ' parameters as shown in Fig. 6b.
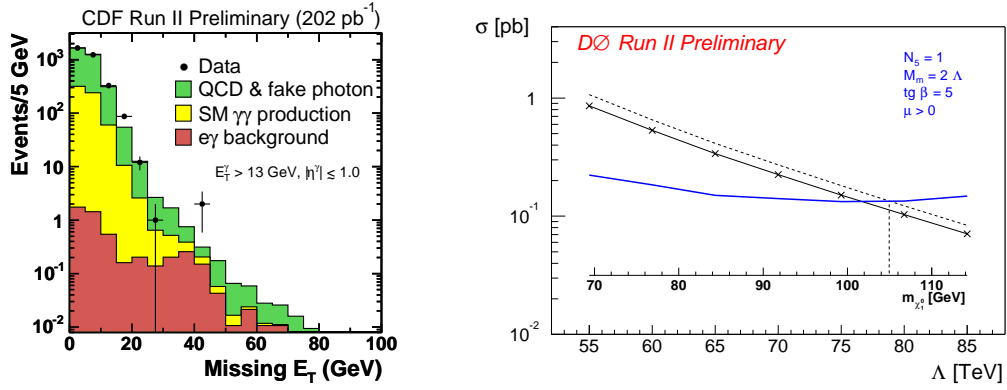
Figure 5: *(a) MET distribution of events accompanied by 2 isolated photons observed by CDF (left). (b) Cross section limit of inclusive 2 photon events with MET > 40 GeV, obtained by DØ and the theoretical cross section of the GMSB model (dotted line indicates NLO calculation).*
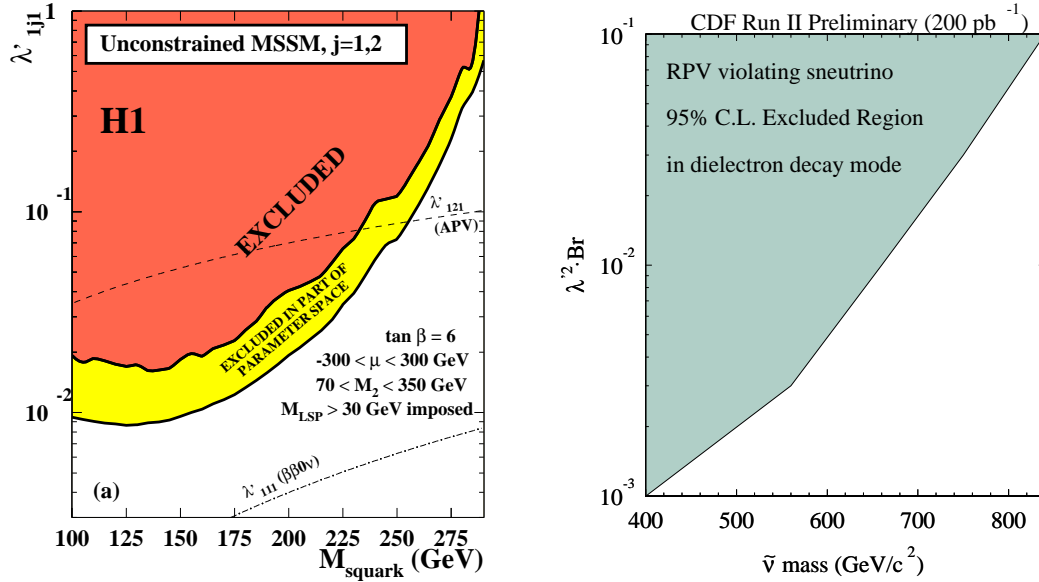

Figure 6: *(a) Exclusion limits on λ'_{1j1}, $j = 1, 2$ as a function of the squark mass. The two full curves indicate the strongest and the weakest limits. Indirect limits from neutrinoless double beta decay ($\beta\beta0\nu$) and atomic parity violation (APV) are also shown. (b) Exclusion of the RPV violating λ' coupling as a function of the $\tilde{\nu}$ mass obtained by CDF. Br is the decay branching ratio of the $\tilde{\nu}$ into an oppositly charged electron pair.*

Table 1: *Z′ mass limits in GeV obtained by the CDF and DØ collaborations*

type	SM coupling	Z_I	Z_χ	Z_ψ	Z_η
CDF	750	570	610	625	650
DØ	780	575	640	650	680

4 Z'

Recurrences of the SM gauge bosons appear in several extension of the SM. For example in the breakdown of the E_6 gauge group in addition to Z_{SM} two other Z's appear: Z_ψ and Z_χ which can be mixed: $Z'(\theta) = Z_\psi \cos\theta + Z_\chi \sin\theta$. Depending on the mixing angle θ, different Z' particles are predicted: Z_ψ, Z_χ, Z_η and Z_I. Both CDF [2] and DØ [1](vii) has searched for signals. In Table 1 the limits on the Z' masses are displayed, derived from the oppositly charged electron pairs.

5 Little Higgs Model

The model proposes new fermions and bosons to solve the hierarchy problem. Contrary to SUSY, here the quadratically divergent diagrams are cancelled by the same type of particle. Z_H is one of the new bosons to cancel divergent boson loops. Its coupling is parametrized by Θ. Using the absence of the resonant structure at high masses in the oppositly charges di-lepton pairs CDF has derived the following limits on the Z_H mass [2]: $M(Z_H) > 800$ GeV for $\cot\Theta = 1$ (electron pairs) and $M(Z_H) > 755$ GeV for $\cot\Theta = 0.9$ (muon pairs).

6 Leptoquarks

Leptoquarks (LQ) are hypothetical bosons (scalars or vectors) which carry both L and B. They are proposed in several extension of the SM based on quark-lepton symmetry. HERA is an ideal machine to produce 1st generation LQ's, in the fusion of the incoming electron and quark. The production is proportional to λ, the Yukawa coupling of the LQ to the lepton and quark it is composed of. Leptoquarks, if exist, would show up as resonances in the invariant mass distribution of the final state lepton and jet. Neither H1 [3](iii) nor ZEUS [4](ii) has observed such signal (see e.g. Fig. 7a). This allows to set limit on the leptoquark mass depending on its nature (i.e. coupling). Examples of limits are shown in Fig. 7b.

At the Tevatron LQ's are dominantly produced in pairs of the same generation. The final state is therefore characterized by 2 jets and 2 leptons, where the
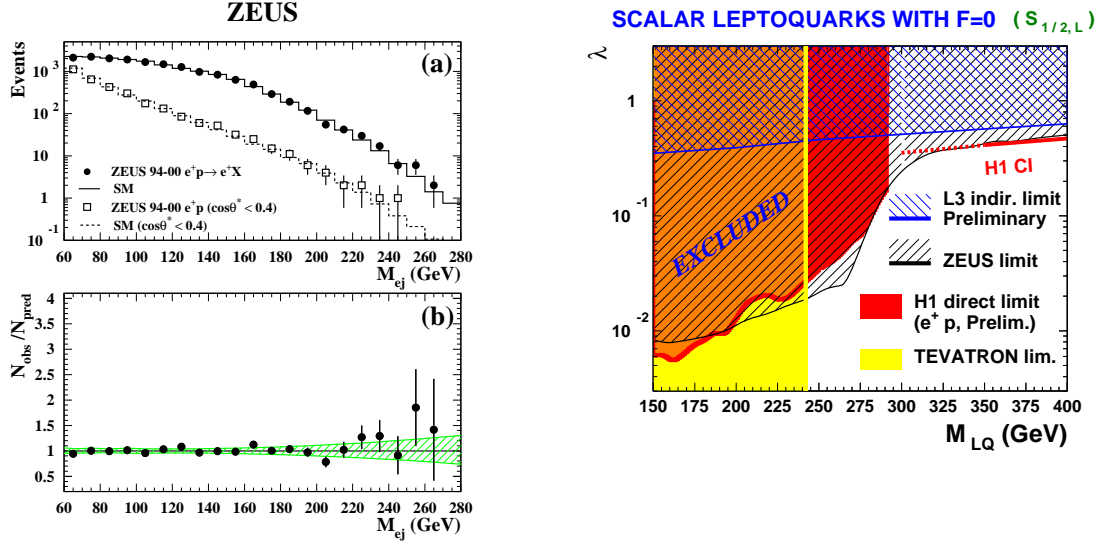
Figure 7: *(a) Invariant mass distribution of the final state electron and jet and its ratio to the SM expectation (left) obtained by the ZEUS collaboration. (b) Exclusion region of leptoquarks as function of their mass and coupling.*
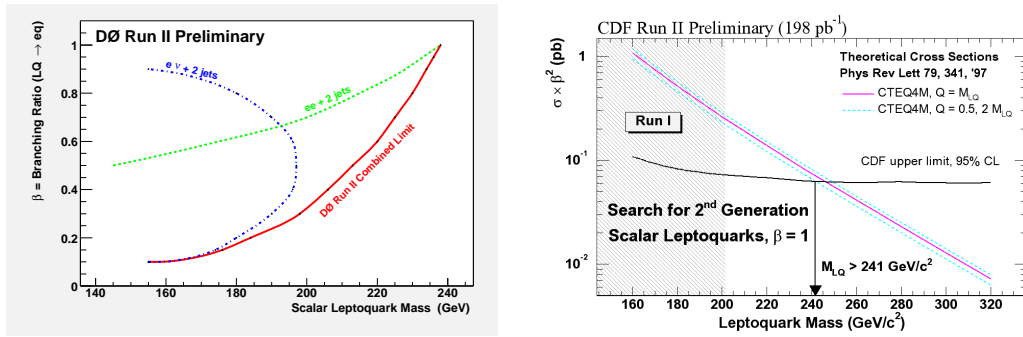

Figure 8: *(a) Combined limit on 1st generation leptoquark mass obtained by DØ (left). (b) Limit on 2nd generation leptoquark mass obtained by CDF (right) with $\beta = 1$.*

leptons can be either charged or neutral, with a branching ratio of β. One studies final states with 2 jets + 2 charged leptons, 2 jets + 1 charged lepton and MET, or 2 jets + MET. The production is independent of λ. The signal dominates the background in regions where the scalar sum of jets and leptons are large. In this region however the observed number of events is compatible with that expected from the background. Using that both DØ [1]($viii$) and CDF [2] has set new lower limits on the leptoquark mass as a function of β, as indicated in Fig. 8a and b.

7 Beyond SM Higgs bosons

Physics beyond the SM may be observed also in the Higgs sector. One searches either for those Higgses which are not predicted by the SM, e.g. SUSY Higgses, double charged Higgses, etc, or for SM-type Higgses with anomalous production cross section or decay rates. DØ has established upper limits for branching ratios for the $h \rightarrow \gamma\gamma$ decay as a function of the Higgs mass [1](ix). CDF [2] and DØ [1](x) have obtained comparable limits on cross section of the Higgs production multiplied by the decay branching ratio into $2W$'s, where both W decays leptonically (see Fig. 9a). DØ has set limits on the SUSY parameter $\tan\beta$ as a function of the mass
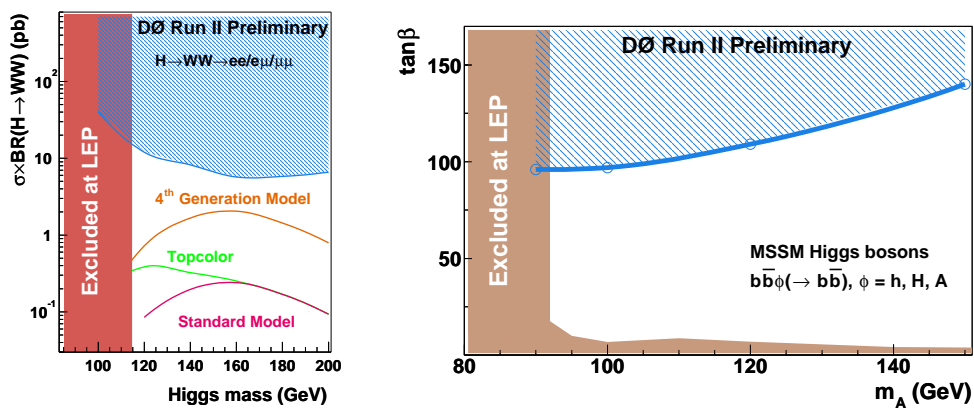

Figure 9: *(a) Limit on the Higgs production cross section multiplied by the decay branching ratio into* $2W$'s, where both W decays leptonically by DØ (left). (b) Limit on $\tan\beta$ as a function of the neutral MSSM Higgs mass (right) obtained by DØ.

of the neutral MSSM Higgs boson [1](xi) (see Fig. 9b). Results from searches for multiple lepton final states performed on both colliders have been interpreted in double charged Higgs bosons scenarios. Although some excess has been found by H1 in the 2e and 3e final states compared to the prediction of the SM [3](iv) (see Fig. 11a), only 1 event agreed with the expected topology of double charged Higgs

production and decay. The ZEUS collaboration didn't observe similar deviation from the SM and neither CDF [2] nor DØ [1](xii) have found excess of multilepton events compatible with the double charged Higgs. All experiments have set lower limit on its mass.

8 Substructure of quarks and leptons

Allowing for internal structure of quarks and leptons goes certainly beyond the SM. Possible substructure can manifest itself either in excited states of quarks and leptons, or in their finite size, or in a contact interaction, the energy scale of which is much larger than the center of mass energy of the reaction. CDF has searched
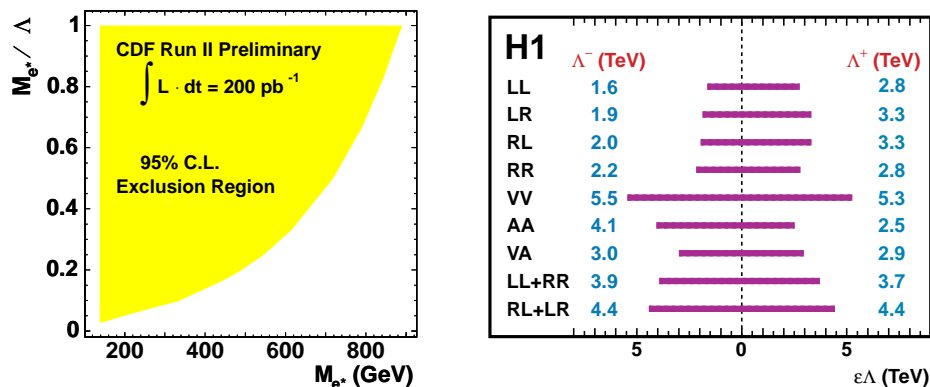

Figure 10: *(a) Exclusion region obtained by CDF for the mass of the excited electron, M_{e^*} and the compositness scale, Λ. (left). (b) Lower limits on the compositness scale parameters $\Lambda^{\pm}$ obtained by H1 in various chiral models (right). $\varepsilon = \pm$ stands for positive or negative interference with the SM.*

for signal of excited electrons in the final state of two isolated electrons and an isolated photon [2]. 3 events were observed and 3.1 events were expected from the SM background. This allowed to exclude excited electrons below masses of 889 GeV depending on the compositness scale Λ as shown in Fig. 10a.

Contact interactions and the size of quarks and leptons have been searched for at HERA [3](i), [4](i). Both H1 and ZEUS have excluded contact interactions up to the scale $\Lambda^{\pm}$ of several TeV's, as shown e.g. in Fig. 10b. By comparing the observed number of events with that predicted by the SM as a function of the 4-momentum transfer squared, Q^2, both H1 and CDF have set upper limit on the radius of the quark, $R_q < 1.0 \cdot 10^{-18}$ m (H1) and $R_q < 0.85 \cdot 10^{-18}$ m (ZEUS), assuming that the electron is pointlike.

9 Searches for anomalies

As already mentioned, H1 has found 6 multi-electron events of high mass, as shown in Fig. 11a, in excess to the SM prediction. At present, there is no explanation for this excess. In addition, H1 has also found 6 events with an isolated lepton (3 events with electrons and 3 with muons), accompanied by high MET and jets of high transverse energy, whereas only 1.3 events are expected from the SM [3](v). A possible explanation of these latter events would be single top production with FCNC coupling. Indeed, 5 events are compatible with this hypothesis and H1 determines the corresponding inclusive cross section $\sigma(ep \to etX) = 0.29 \pm 0.15$ pb. ZEUS does not observe that phenomenon and it determines exclusion contour for the $tu\gamma$ and tuZ FCNC couplings [4](iii).

H1 has also undertaken a systematic, model independent search for anomalies [3](vi). It selects events with at least 2 isolated objects among electrons, muons, photons, jets and MET with $E_T > 20$ GeV, and compares the number of observed events with that predicted in different bins of their invariant mass distribution or of their sum of p_T spectrum. As shown in Fig. 11b, significant deviation from the SM has observed only in the $\mu - j - \nu$ channel.
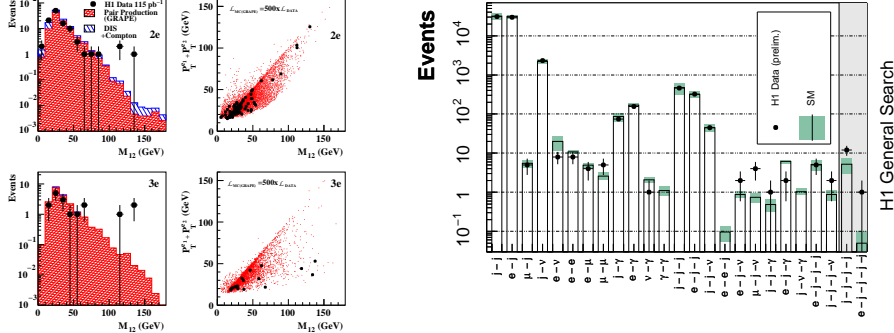

Figure 11: (a) Distribution of the invariant mass M_{12} of the two highest p_T electrons (left) and the correlation between M_{12} and the sum of p_T's (middle). Large size dots are the data, histogram and small size dots represent the SM (with scaled up luminosity). (b) Number of observed events (data points) and expected number of events from the SM (squares) in different event categories selected by H1 (right).

10 Conclusion

The performances of both Tevatron and HERA improve steadily allowing to test new ideas of ever increasing number in the search of the ultimate theory of matter.

13

Although some anomalies have been observed, no conclusive sign for new beyond SM physics has appeared yet. More results are expected soon, already at the late summer conferences of this year.

11   Acknowledgements

References

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2. CDF Collaboration `http://www-cdf.fnal.gov/physics/exotic/exotic.html`.

3. H1 Collaboration `http://www-h1.desy.de/` (*i*) DESY 03-052 May 2003, (*ii*) DESY 04-025, March 2004, (*iii*) H1 0105 for Conf LP03, (*iv*) DESY 03-082 July 2003, (*v*) DESY 02-224 2002 january 2003, and H1 0079 for Conf LP03, (*vi*) H1 0118 for Conf LP03.

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5. For the meaning of the SUSY parameters see e.g. ATLAS Detector and Physics Performance Technical Design report, Vol II. CERN/LHCC/99-15, ATLAS TDR 15, 25 May 1999.